GLAN-THOMPSON TYPE BROADBAND POLARIZER DEVICE FOR USE IN THE DEEP ULTRAVIOLET SPECTRAL RANGE AND METHOD OF ITS MANUFACTURE

FIELD OF THE INVENTION

This invention relates to a polarizer device and method of its manufacture.

BACKGROUND OF THE INVENTION

Polarizers are optical elements used to determine the direction of the electric field of an electromagnetic wave. Most radiation sources including all natural sources are unpolarized sources. If polarizer is located in the optical path of an unpolarized light beam, the polarizer output will mainly contain only one of the two linear orthogonal polarization components of the input beam, depending on the preferred axis of the polarizer. The ratio between the energy of the un-preferred polarization component and that of the preferred polarization component in the output light beam is usually valued by the polarizer's extinction ratio.

Polarizers are required in a large range of optical systems, including among others ellipsometers. Polarizers can be implemented from a variety of materials, including polymers, crystals, organic and inorganic compounds. Polarizers frequently used in optometry and photography are made of polymers. They, however, do not operate in Deep UV (DUV), which is important for example for spectrometric measurements.

Mostly used DUV-transmitting materials are in fact crystals. Polarizers are made of birefringent crystals. With a birefringent crystal, a light beam with a polarization vector parallel to the optical axis of the crystal ("Extra-Ordinary ray") will experience a different (usually lower) index of refraction, n_e, compared to that of a beam with a polarization vector perpendicular to the optical axis of the crystal ("Ordinary rays"), n_o.

There are several types of polarizers based on matching two prisms made of birefringent materials. The operation of some of these polarizers, including Glan-Thompson and Glan-Taylor type polarizers, is based on the principle of total internal reflection (TIR). **Figs. 1A and 1B** illustrate the configuration and operational principles of such polarizers. As shown, the polarizer is formed by two prisms P_1 and P_2 (typically of a rectangular triangle cross section) attached to each other by their tilted surfaces S_1 and S_2, respectively. In the Glan-Thompson type polarizer, the surfaces S_1 and S_2 are spaced from each other by optical glue, such as "WELD-ON 3" commercially available from IPS Corporation or NOA 61, commercially available from Norland Products Inc.

According to Snell's law of refraction, an input light beam which impinges from a first medium (prism P_1) onto an interface between the first and second media (prisms P_1 and P_2) with an angle of incidence θ_1, is refracted at the interface and enters the second medium (prism P_2) with the angle of incidence θ_2, which is given by:

$$n_1 \cdot \sin(\theta_1) = n_2 \cdot \sin(\theta_2) \qquad (1)$$

where n_1 and n_2 are the indices of refraction of the first and second media, respectively.

Total internal reflection occurs when $n_1 > n_2$ and θ_1 is sufficiently large. Extracting $\sin(\theta_2)$ from equation (1), results in:

$$\sin(\theta_2) = (n_1/n_2) \cdot \sin(\theta_1) \qquad (2)$$

If $\sin(\theta_1) > (n_2/n_1)$, than $((n_1/n_2) \cdot \sin(\theta_1)) > 1$ and there is no solution for θ_2. In this case, no light will pass the interface and 100% of the input light will be reflected back into the first medium.

Glan type polarizers use the above effect in the following way: A prism P_1 is made of a birefringent crystal, and is oriented with respect to an input light beam such that the preferred axis of the crystal (its optical axis) is parallel to the direction D_1 of propagation of the input beam. Ordinary and extraordinary rays R_o and R_e of the input beam experiences different indices of refraction n_o and n_e of the birefringent crystal. For a light beam impinging onto the input surface of the prism with the zero angle of incidence, none of the ordinary and extraordinary rays is refracted at the input surface of the prism. Inside the prism, these rays are incident on a tilted output surface (surface S_1) of the prism. If an angle between the tilted interface S_1 and the direction of incident

beam propagation (which defines the angle of incidence θ of the input beam onto the surface S_1 and which is defined by the cut angle θ' of the prism) is chosen such that only one of the rays (e.g., R_e) is reflected by total internal reflection while the other (R_o) passes through this interface and emerges from the prism P_1, then the required polarization effect is achieved (i.e., linearly polarized output beam R_o). In order to direct the output beam in the original direction D_1 of the input beam and avoid spectral dispersion, a second prism P_2 is used.

Considering n_2 is a refractive index of the medium between the two prisms (air in the Glan-Taylor type polarizer and optical glue in the Glan-Thompson polarizer), the polarization effect can be achieved when the condition $\sin(\theta)>(n_2/n_o)$ is satisfied for the ordinary ray only (assuming $n_e<n_o$. Hence, the following condition is typically taken into account when designing a polarizer:

$$1/n_o<\sin(\theta)/n2<1/n_e \qquad (3)$$

which is typically adjusted by solely varying the value of the cut angle θ'.

SUMMARY OF THE INVENTION

There is a need in the art to facilitate polarization effect within a broad spectral range (including DUV) with a single polarizer assembly. Various applications require high transmission and high extinction ratio of the polarizer assembly over the whole spectral range at the same time.

Glan-Taylor polarizer has a limited angular field when used for broad spectral band, because the refractive index of air is constant, while the indices of refraction n_e and n_o of the prism depend on wavelengths of the input light (i.e., have certain dispersion profiles). As a result, the operation of this polarizer is limited by the value of angle θ'. As for Glan-Thompson polarizer, its operation depends critically on the properties of the glue between the two prisms, therefore the operation of this polarizers is limited by a specific, practically narrow, usually visual only or DUV spectral range. For example, WELD-ON 3 commercially available from IPS Corporation and NOA 61, commercially available from Norland Products Inc. provide for operating in a visual spectral range.

The present invention solves the above problem by providing a polarizer configuration generally similar to the Glan-Thompson prism polarizer or Glan-Thompson splitter (i.e., optical glue between two crystal prisms), where such parameters as a material of the polarizer prisms, the prisms' configuration (the so-called "cut angle" of the prism), and a glue material, are selected so as to ensure total internal reflection of one of the ordinary and extraordinary beam components of input light for the broadband input light, namely including DUV spectral range (from about 190nm).

The prisms are made of a birefringent material and are configured such that the preferred axis of the prism material forms a predetermined angle (cut angle of the prism) with the tilted surface of the prism by which it is coupled to the other prism.

The glue material is selected so as to be characterized by a dispersion profile (its refraction index n_g as a function of wavelength) matching that of the polarizer prisms' material (crystal) for extraordinary and ordinary polarization axis (refraction indices n_e and n_o as functions of wavelength) in the broadband spectral range. The selected glue composition has to be stable over time when exposed to variations in environmental conditions (temperature variations, UV radiation, etc.).

An additional potential problem when designing the polarizer is associated with absorption/scattering properties of the glue. To this end, the glue layer is to be desirably thin. The minimal possible thickness of the glue layer is determined by the effective "skin-depth" inside the glue, which is defined by the refractive index of the glue and the refractive index of the polarizer prisms' material for the selected one of the ordinary or extraordinary beam component which is to be passed through (refracted by) the entire polarizer. Preferably, in order to desirably minimize the thickness of the glue layer (a thickness of a few microns, e.g., 5-10 microns) while maintaining the uniformity of the layer thickness, the present invention utilizes mixing the glue material with small solid transparent particles (beads), made for example from glass or plastic. The number of the beads in the glue layer is defined by the requirement to minimize the glue layer absorption of DUV radiation. These small beads (with the diameter of about 5-10 microns) should preferably be distributed within the surface area of the glue layer with

the area concentration C_s not exceeding $10^{-6}cm^{-2}$, and thus the volume concentration, C_v, of the beads in the glue is to be lower than $10^{-9}cm^{-3}$.

Considering the polarizer prisms are α-BBO crystals, the preferred glue material is a two-part RTV Silicone transparent to electromagnetic radiation within a wide spectral range including short wavelength of about 190nm. Such glue may be controlled volatility, low viscosity, low outgassing glue of the type CV15-2500, commercially available from NuSil Technology, USA. This glue material has a 1.41 refractive index in visual spectral range, and a 50μm layer of the glue has about 95% transparency.

Preferably, in order to minimize the footprint of the polarizer while not affecting its operation, the side facets of the polarizer (light input and output facets) are of circular geometry or a polygon of more than four angles (e.g., eight-angle polygon).

There is thus provided according to one broad aspect of the present invention, a polarizer device of Glan-Thompson type comprising:

- first and second prisms made of a birefringent material having certain dispersion profiles $n_o(\lambda)$ and $n_e(\lambda)$ for, respectively ordinary and extraordinary polarization axis and being coupled to each other by a binding material layer, wherein said binding material has a dispersion profile, $n_g(\lambda)$, matching said dispersion profiles $n_o(\lambda)$ and $n_e(\lambda)$ so as to provide an effect of total internal reflection within a spectral range including short wavelength of about 190nm.

According to another broad aspect of the present invention, there is provided a polarizer device of Glan-Thompson type comprising:

first and second prisms made of a birefringent material having certain dispersion profiles $n_o(\lambda)$ and $n_e(\lambda)$ for, respectively ordinary and extraordinary polarization axis and being coupled to each other by a binding material layer including a mixture of a binding material and small beads of a solid transparent material, wherein said binding material has a dispersion profile, ng(λ), matching said dispersion profiles $n_o(\lambda)$ and $n_e(\lambda)$ so as to provide an effect of total internal reflection within a spectral range including short wavelength of about 190nm.

According to yet another broad aspect of the present invention, there is provided a polarizer device comprising:

- first and second prisms made of a birefringent material having certain dispersion profiles $n_o(\lambda)$ and $n_e(\lambda)$ for, respectively ordinary and extraordinary polarization axis and being coupled to each other by a binding material layer including a mixture of a binding material and small beads of a solid transparent material, wherein said binding material has a dispersion profile, $n_g(\lambda)$, matching said dispersion profiles $n_o(\lambda)$ and $n_e(\lambda)$ so as to provide an effect of total internal reflection within a spectral range including short wavelength of about 190nm and wherein the beads being substantially uniformly distributed within the binding material layer with a surface area concentration, Cs, substantially not exceeding 10-6cm^{-2}.

According to yet another aspect of the present invention, there is provided a polarizer device comprising:

- first and second prisms coupled to each other by their tilted surfaces; and

a binding material layer between said tilted surfaces of the prisms, said layer including a mixture of a binding transparent material and small beads of a solid transparent material, the binding material layer thereby having a substantially uniform thickness of about 5-10 microns.

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According to yet another aspect of the present invention, there is provided a polarizer device having opposite side facets serving for, respectively, inputting and outputting light, wherein each of said side facets is either a circle or a polygon of more than four angles.

According to yet another broad aspect of the present invention there is provided a method of manufacturing a polarizer device of Glan-Thompson type comprising providing first and second prisms made of a selected birefringent material having certain dispersion profiles $n_o(\lambda)$ and $n_e(\lambda)$ for, respectively ordinary and extraordinary polarization axis, selecting a binding material having a dispersion profile, $n_g(\lambda)$, matching said dispersion profiles $n_o(\lambda)$ and $n_e(\lambda)$ so as to provide an effect of total internal reflection within a spectral range including short wavelength of about 190nm and attaching the tilted surfaces of the prisms to each other by a layer of said binding material.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, a preferred embodiment will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Figs. 1A and 1B show the configuration and operational principles of a conventional double-prism polarizer;

Fig. 2 illustrates a polarizer device of the present invention;

Figs. 3A to 3C graphically illustrate the principles of the present invention for designing an α-BBO polarizer device, wherein **Fig. 3A** shows the total reflection angle of the prism as a function of wavelength of input light for 1.4 refractive index of a glue layer between two α-BBO crystal prisms, **Fig. 3B** shows the dispersion profile of the glue layer, and **Fig. 3C** shows the optimal conditions for the polarizer configuration;

Fig. 4 shows the minimal and maximal dispersion profiles for a glue material suitable to be used in a polarizer device with the cut angle of 30.4°, and the dispersion profile of a specific glue material available in the market;

Fig. 5 illustrates yet another principle of the invention for designing a polarizer device, showing a skin-depth in glue layer versus wavelength of input light;

Fig. 6 illustrates another example of a polarizer device of the present invention; and

Figs. 7A-7D illustrate yet another advantageous feature of the present invention, wherein Figs 7A-7B show the typical shape of the convention polarizer, and Figs. 7C-7D show that of the polarizer of the present invention aimed at minimizing the footprint of the polarizer while not affecting its operation.

DETAILED DESCRIPTION OF THE INVENTION

Figs. 1A and 1B illustrate the configuration and operation principles of a conventional polarizer device of Glan-Tailor type (two prisms mechanically coupled to each other with an air gap between them) or Glan-Thomson type (two prisms glued to each other).

The present invention provides for a novel polarizer device suitable to be used for extracting either one of ordinary or extraordinary polarization component of input light or splitting thereof within a broadband spectral range of the input light, i.e., including DUV (about 190nm) to IR (950nm) and longer.

Referring to **Fig. 2**, there is schematically illustrated a polarizer device **10** of the present invention. The device **10** of Glan-Thomson type is formed by two prisms $\mathbf{P_1}$ and $\mathbf{P_2}$ attached to each other by an optical glue layer **12** between the tilted surfaces of $\mathbf{S_1}$ and $\mathbf{S_2}$ of the prisms $\mathbf{P_1}$ and $\mathbf{P_2}$, respectively. In this device, the following parameters are appropriately selected to ensure the device operation for light within the spectral range of about 190nm-950nm: cut angle **θ'** of the prism; and the properties of the glue material layer **12**.

The prisms $\mathbf{P_1}$ and $\mathbf{P_2}$ are made of a birefringent material that is transparent for the required broadband spectral range, and is preferably α-BBO or quartz. The prisms are configured such that the preferred axis **PA** of the prism material forms a predetermined angle θ' (cut angle) with the tilted surface $\mathbf{S_1}$ of the prism $\mathbf{P_1}$ by which it is coupled to the other prism $\mathbf{P_2}$. The glue material for the layer **12** is selected so as to be characterized by a dispersion profile $n_g(\lambda)$ matching the dispersion profiles $n_e(\lambda)$ and $n_o(\lambda)$ of the prism material for, respectively, extraordinary and ordinary rays $\mathbf{R_o}$ and $\mathbf{R_e}$ in the required spectral range. Moreover, the glue material is selected to be stable over time when exposed to variations in environmental conditions (temperature variations, UV radiation, etc.). For α-BBO crystal prisms, the preferred glue material is a two-part RTV Silicone transparent to electromagnetic radiation ranging from 190nm to 800nm. Such glue may be controlled volatility, low viscosity, low outgassing glue CV15-2500, commercially available from NuSil Technology, USA (a 50μm layer of this glue has about 95% transparency).

Reference is now made to **Figs. 3A-3C** illustrating the principles of the present invention for designing a α-BBO polarizer device.

Let us assume that the refractive index of the glue is constant over all wavelength (i.e., the glue material has no dispersion), for example is about 1.4. **Fig. 3A** shows the total reflection angles θ_o and θ_e for the ordinary and extraordinary polarization

components of the input beam in the prism as functions of wavelength of the input beam for 1.4 refractive index glue layer between two α-BBO crystal prisms. For the proper operation of a polarizer device, the angle of incidence θ of the input beam with respect to the tilted surface $\mathbf{S_1}$ of the prism $\mathbf{P_1}$ must be between the curves $\theta_o(\lambda)$ and $\theta_e(\lambda)$ of the total internal reflection for ordinary and extraordinary rays of this input beam. To this end, a finite conjugate situation is to be considered and the fact that the input beam has a certain beam divergence. In other words, the angle of incidence θ of the input beam, namely, the cut angle of the prism (considering that the prism when in use is oriented such that the beam impinges onto the prim along its optical axis) should be selected such that enough margins M_1 and M_2 are provided between the angle θ and angles θ_o or θ_e within the required spectral range for the device operation. As can be seen in Fig. 3A, a certain problem might be in a spectral range below 230nm and also at the upper spectral range slightly above 1000nm. For α-BBO polarizer device with 1.4 refractive index glue layer, the optimal angle of incidence θ is about 59-60° (preferably 59.6°), the cut angle being θ'=(90-θ).

While selecting glue material having an optimal dispersion profile, as shown in **Fig. 3B**, the cut angle of the prism, and accordingly the angle of incidence θ, would match the TIR conditions of the ordinary and extraordinary rays, $\theta_o(\lambda)$ or $\theta_e(\lambda)$, as shown in **Fig. 3C**.

Generally speaking, the glue material should be selected such that its dispersion profiles for ordinary and extraordinary rays $n^{(g)}{}_o(\lambda)$ or $n^{(g)}{}_e(\lambda)$ match the dispersion profiles of the prism material, $n^{(p)}{}_o(\lambda)$ or $n^{(p)}{}_e(\lambda)$. **Fig. 4** shows the minimal and maximal dispersion profiles G_1 ($n^{(g)}{}_o(\lambda)$) and G_2 ($n^{(g)}{}_e(\lambda)$), respectively, for a glue material suitable to be used in a polarizer device with the cut angle θ'=30.4° (θ'=90-59.6°). The inventors have found that CV15-2500, commercially available from NuSil Technology, USA has the dispersion profile (graph G_3) satisfying this requirement.

Furthermore, the glue layer should preferably be sufficiently thin (a few microns, e.g., 5-10 microns) to avoid undesirable light absorption in the glue (which is essential for DUV spectral range). The minimal possible thickness of the glue layer is determined by the effective "skin-depth" inside the glue, which is defined by the refractive index of

the glue and the refractive index of the polarizer prisms' material for the selected one of the ordinary or extraordinary beam component which is to be passed through (refracted by) the entire polarizer. In other words, the glue layer should not be too thin to avoid "tunneling".

With the refractive index of ordinary ray for α-BBO being n_{ord} and that of the glue being n_{glue}, and the incidence angle θ=59.5°, the rate of decay of light inside the glue can be estimated as follows:

The lateral component of the k-vector at the crystal (which must also be inside the glue) is:

$$k_x = n_{ord} k_0 \sin\theta_{inc}$$

The total k-vector length inside the glue is $n_{glue}k_0$, therefore the component of the vector inside the glue that is normal to the plane must be:

$$\begin{aligned} k_{z,glue} &= k_0\sqrt{n_{glue}^2 - n_{ord}^2 \sin^2\theta_{inc}} \\ &= -jk_0\sqrt{n_{ord}^2 \sin^2\theta_{inc} - n_{glue}^2} \end{aligned}$$

Since the field inside the glue depends on z (axis normal to the plane of beam propagation) according to

$$\exp(jk_z z) = \exp\left(-k_0 z\sqrt{n_{ord}^2 \sin^2\theta_{inc} - n_{glue}^2}\right) = \exp(-z/\delta)$$

the effective "skin-depth" δ inside the glue is:

$$\delta = \frac{1}{k_0\sqrt{n_{ord}^2 \sin^2\theta_{inc} - n_{glue}^2}}$$

Fig. 5 illustrates a plot of this skin-depth versus wavelength: For a proper operation, actual glue thickness should be about 10 times this value δ, giving for entire

range of wavelengths up to 950nm a minimum thickness of about 6 microns. This parameter depends on the maximal wavelength of the required spectral range.

The glue layer should thus be desirable thin and with the uniform thickness along the layer.

Fig. 6 exemplifies a polarizer device **100** in which the uniformly thin glue layer **112** is obtained by mixing a glue material (selected as described above) with small solid transparent particles (beads) **114**, made for example from glass or plastic. The concentration of the beads **114** in the glue layer **112** is defined by the requirement to minimize the glue layer absorption of DUV radiation. The small beads (with the diameter of about 5-10 microns) are preferably distributed within the surface area of the glue layer with the area concentration C_s not exceeding $10^{-6}cm^{-2}$, and thus the volume concentration, C_v, of the beads in the glue is lower than $10^{-9}cm^{-3}$. Such concentration enables negligible effect of particles on the polarizer performance.

It is often the case that an optical system should be of as small footprint as possible (for example in integrated metrology/inspection tools). The present invention provides for solving this problem by designing a polarizer with its side facets (input and output facets) as a circle or polygon of more than four angles, rather than a typically used rectangle. This is illustrated in **Figs. 7A-7D**.

Fig. 7A shows a typical shape of a polarizer device having rectangular input and output facets $\mathbf{F_1}$ and $\mathbf{F_2}$. As shown in **Fig. 7B**, the dimensions of this facet $\mathbf{F_1}$ (and $\mathbf{F_2}$) define the maximal spot size diameter of the output beam and the minimal footprint of this polarizer.

Figs. 7C and 7D illustrate a polarizer device **200** of the present invention. The device **200** has side facets $\mathbf{F'_1}$ and $\mathbf{F'_2}$ in the form of a polygon with more than 4 angles – eight-angle polygon in the present example. It should be understood that the best case would be a circular geometry of the side facets, but this is more difficult to implement. As can be seen from **Fig. 7D**, this polarizer is characterized by smaller footprint for the same spot size of the output beam, as compare to that of Figs. 7A-7B.

Those skilled in the art will readily appreciate that various modifications and changes can be applied to the embodiments of the invention as hereinbefore exemplified without departing from its scope defined in and by the appended claims.